

High-velocity clouds: a diverse phenomenon

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Abstract. In this contribution the current state of knowledge about the high-velocity clouds (HVCs) is summarized. Recent progress has shown that the HVCs are a diverse phenomenon. The intermediate-velocity clouds (IVCs) are likely to be part of a Galactic Fountain. The Magellanic Stream is a tidal remnant. HVC complex C (possibly complexes A and GCN) are low-metallicity clouds near the Galaxy; they could be remnants of the formation of the Galaxy or old tidal streams extracted from nearby dwarf galaxies. Having a substantial number of HI HVCs dispersed throughout the Local Group seems incompatible with the observed HI mass function of galaxies. Finally, FUSE finds high-velocity O VI, some of which is clearly associated with HI HVCs, but some which is not.

1 Introduction

The HVCs and IVCs consist of gas moving at velocities incompatible with a simple model of differential galactic rotation. Wakker[20] defines the “deviation velocity” (v_{dev}) as the difference between the observed LSR velocity and the maximum velocity that can be understood in terms of galactic rotation. With this definition HVCs have $|v_{\text{dev}}| > \sim 90 \text{ km s}^{-1}$, while IVCs have $|v_{\text{dev}}| = 30\text{--}90 \text{ km s}^{-1}$.

Maps of the large-scale structure of HVCs[21] in 21-cm HI emission are based on four surveys. Two of these[2, 9], cover the sky on a $1^\circ \times 1^\circ$ grid ($2^\circ \times 2^\circ$ for declinations $< -18^\circ$), down to a column density of $\sim 2 \times 10^{18} \text{ cm}^{-2}$, though only at 16 km s^{-1} velocity resolution. The Leiden-Dwingeloo Survey (LDS[8]) and its southern equivalent[1, 14] cover the sky on a $0.5^\circ \times 0.5^\circ$ grid, at 1 km s^{-1} velocity resolution, but only down to about $8 \times 10^{18} \text{ cm}^{-2}$.

Most of the recent progress in understanding the origin of the HVCs and IVCs has been made through measurements of distances and metallicities. Wakker[21] summarizes the available literature up to mid 2001. Below, a short summary is given of each of the origins for which observational evidence now exists.

2 Intermediate-Velocity Clouds

Distance measurements exist for several IVCs: the IV-Arch ($z=0.7\text{--}1.7 \text{ kpc}$), the LLIV-Arch ($z=0.9 \text{ kpc}$), complex K ($z<4.5 \text{ kpc}$) and the PP-Arch ($z<0.9 \text{ kpc}$). All of these show metallicities of 0.5–1 times solar. FUSE data of extragalactic targets show O VI absorption at IVC velocities in many cases and in

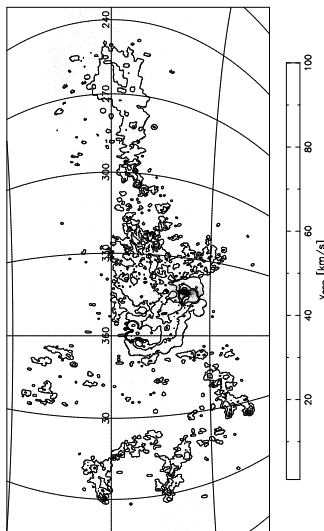


Figure 1: Map of the Magellanic Stream (from [9, 14]). The greyscale shows velocities, as identified by the wedge. Intensity contours show column densities of 2, 25, 75 and $350 \times 10^{18} \text{ cm}^{-2}$. Dots shows the current particle positions in the model of Gardiner & Noguchi[5], while solid lines show the orbits of the LMC and SMC in this model.

few of these, the O VI absorption appears to be centered at the same velocity as the HI of the IVC. However, it is not always clear whether the O VI is associated with the IVC, or whether the Galactic O VI component is just broad. For the two IVC sightlines have been studied in detail (PG 0804+761[16] and PG 1259+593[17]) the properties of the gas (distance, metallicity, ionization structure, the presence of hot gas) are compatible with the notion that the IVCs are a manifestation of the Galactic Fountain.

3 The Magellanic Stream

The Magellanic Stream is comparatively well understood. For a while it seemed possible that the Stream is the result of ram-pressure stripping[13], but since the identification of the leading arm[11] the tidal model is clearly favored. Two measurements of S II/H I in the Stream exist. Toward NGC 3783, $(l,b)=(287^\circ,+23^\circ)$, Lu et al.[11] found a value of 0.25 ± 0.07 times solar, while toward Fairall 9, $(l,b)=(295^\circ,-58^\circ)$ Gibson et al.[6] find 0.33 ± 0.05 times solar. In the most complete published model[5] the combined tidal force of the LMC and Galaxy on the SMC peaked 2 Gyr ago, during their previous peri-galacticon passage. As a result about $2.5 \times 10^8 M_\odot$ of material (out of an original total of $8 \times 10^8 M_\odot$ [18]) was extracted from the outer parts of the

SMC. One orbit later the MCs are again near perigalacticon, now followed by a trailing tidal arm (the Magellanic Stream, $M=1.5\times10^8 M_\odot$) and a leading arm ($M=10^8 M_\odot$). Figure 1 presents a map of the HI in the Magellanic System, in a coordinate system where galactic longitude $l=270^\circ$ runs along the equator.

4 Complexes A and C

Complex A is the only HVC with a known distance. A bracket of 4–10 kpc was derived by van Woerden et al.[19]. A FUSE spectrum of the star PG 0832+675 improves this to 8–10 kpc. This implies a gaseous mass of $2\times10^6 M_\odot$ (including a correction for He and assuming a 20% ionized fraction). So far, its metallicity is unknown, but FUSE spectra of two extra-galactic objects suggest a value <0.2 times solar, although contamination by H_2 lines is a major problem.

The second largest HVC is complex C. A map of its very complex velocity field is presented by Wakker[21]. Its distance is still fairly uncertain, but probably between 5 and 20 kpc, implying a total mass of $3\text{--}50\times10^6 M_\odot$. Its metallicity is comparatively well-known. Initially, Wakker et al.[22] measured the Sulphur abundance in the direction of Mrk 290 ($N(\text{HI})=9\times10^{19} \text{ cm}^{-2}$) as $(\text{S}/\text{H})=0.09\pm0.02\pm0.02$ times solar. Here the first error is statistical and the second systematic, and this value takes into account H^+ , S^{+2} and HI small-scale structure. Sulphur is a good element to use in this game, as (a) it is mostly undepleted onto dust grains, (b) S^+ is the dominant ionization stage in the diffuse ISM and (c) the S II $\lambda\lambda 1250, 1253$ and 1259 lines are neither too strong nor too weak. Oxygen is also good, as its ionization is strongly tied to that of hydrogen, although some oxygen may be depleted onto dust.

Richter et al.[17] measured abundances in the spectrum of PG 1259+593 ($N(\text{HI})=9\times10^{19} \text{ cm}^{-2}$) and found: $\text{N I}/\text{H I}=0.012\pm0.005$, $\text{O I}/\text{H I}=0.09^{+0.13}_{-0.05}$, $\text{Al II}/\text{H I}=0.10^{+0.11}_{-0.07}$, $\text{Si II}/\text{H I}=0.12^{+0.11}_{-0.05}$, $\text{S II}/\text{H I}=0.14\pm0.04$ and $\text{Fe II}/\text{H I}=0.054^{+0.032}_{-0.015}$ times solar. On the other hand, Gibson et al.[7] found that $\text{S II}/\text{H I}=0.33\pm0.05$ toward Mrk 817 ($N(\text{HI})=3\times10^{19} \text{ cm}^{-2}$) and $\text{N I}/\text{H I}=0.039\pm0.007$ toward Mrk 876 ($N(\text{HI})=1\text{--}2\times10^{19} \text{ cm}^{-2}$). In the latter sightline, Murphy et al. [15] also found $\text{Fe II}/\text{H I}=0.48\pm0.20$, although a large ionization correction is expected because $N(\text{HI})$ is low. Yet, a factor 10 is difficult to reconcile with the non-detection of $\text{H}\alpha$ emission. Further, toward Mrk 290 a STIS spectrum shows that in this sightline $\text{Fe II}/\text{H I}=0.52\pm0.04$, while the FUSE spectrum of Mrk 817 gives $\text{Fe II}/\text{H I}=0.19\pm0.05$ and $\text{O I}/\text{H I}=0.19$ times solar. These abundances shows several interesting patterns.

(1) They clearly confirm the low metallicity of complex C found by Wakker et al.[22]. There is some evidence for variations in the metallicity across the cloud, considering the two different values found for $\text{O I}/\text{H I}$ and $\text{S II}/\text{H I}$. Measurements in more directions will be necessary to understand this.

(2) In both the PG 1259+593 and the Mrk 817 sightline the $\text{S II}/\text{O I}$ ratio is ~ 1.5 times solar, suggesting either that O I is somewhat depleted onto dust, or that a substantial fraction of the hydrogen is ionized.

(3) Two elements that are usually lightly depleted (Al and Si) seem to be undepleted in complex C, as the ratios Al/(O,S) and Si/(O,S) are $>$ solar. This suggests that there is little or no dust present.

(4) Iron still appears depleted in three sightlines: Fe II/S II lies in the range 0.4–0.6 times solar for Mrk 290, Mrk 817 and PG 1259+593. This may mean that either there is some dust made exclusively of iron particles, or that the Fe/S ratio in complex C is intrinsically subsolar.

(5) Nitrogen is clearly underabundant in complex C. Toward PG 1259+593 an improved FUSE spectrum also allows us to measure the N II- λ 1083 line, which shows that $N(\text{NI}) \sim N(\text{NII})$. The intrinsic N/O ratio can be approximated by $\text{NI/OI} \sim 0.15$. This can be compared with value for N/O measured in irregular galaxies[10], in the outer parts of normal spirals[4] and in Damped Ly α Absorbers[12], which shows that only in the latter kind of object are values found that are as low as in complex C.

Taken together, the abundances and ratios are compatible with the notion that complex C consists of gas in which heavy elements were produced only by Type II SNe, explaining the low Fe and N abundances, the high ratios of α -element abundances (Si, S) over O, as well as the apparent absence of dust.

5 HI HVCs in the Local Group?

Blitz et al.[3] proposed that most HVCs are intra-Local-Group clouds, assuming (a) that they contain dark matter and (b) have a median distance of 1 Mpc. Possibly the subset of smaller, compact HVCs forms this population. In this model each HVC is assumed to be self-gravitating and its distance and mass can be derived from observables (velocity dispersion, area and flux) using the virial theorem, assuming a value for f , the ratio of the HI mass to the total mass (HI+H⁺+He+dark matter). Blitz et al. favor $f=0.1$.

Figure 3 shows the resulting HI mass function for the subset of compact HVCs, for $f=0.1$ (thin dotted line) and $f=0.01$ (thick dotted line). These distributions are compared to the HI mass function of the Local Group (lower solid line) and of the general field derived from a deep Arecibo survey[23], scaled to match the Local Group at $M(\text{HI}) > 10^9 M_{\odot}$ (upper solid line).

Clearly, if the HVCs are virially stable and have $f=0.1$, there would be 10–50 times more massive HVCs in the Local Group than galaxies. There would also be 50–200 times more than in a comparable volume outside groups. There are four ways to reconcile this discrepancy. First, the Local Group may be unusual and indeed have many more massive starless HI clouds than the general field. Second, the field HI mass function may have been underestimated by a factor ~ 10 . Third, the value of f may 0.01 or lower (e.g. by increasing the ionization). However, this implies that most distances are in the range 20–200 kpc, and the HVC ensemble would not fill the Local Group, but rather be concentrated around the Milky Way. None of these three possibilities seems likely. Fourth, only a small fraction of the HVC sample may be Local Group

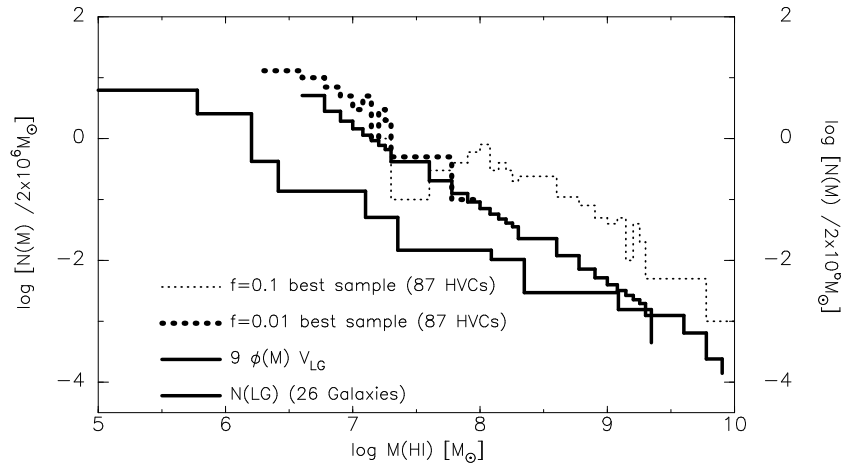


Figure 2: HI mass function of the Local Group (lower solid line), of the general field (upper solid line, scaled by a factor 9 to match the Local Group at high masses), and of the HVC sample assuming $f=0.1$ (thin dotted line) and $f=0.01$ (thick dotted line).

objects. For $f=0.1$ there might be up to 5–10 such objects without causing a discrepancy. For lower f proportionally more are allowed to exist.

6 High-velocity O VI

In its first two years of operation, FUSE has observed 219 extra-galactic objects. Of the 154 observations that were public as of September 2001, a reasonable measurement of Galactic O VI absorption can be obtained in 85 cases (Wakker et al. & Sembach et al., in preparation). In 56 of these sightlines high-negative or high-positive velocity O VI is found. There is clearly high-velocity O VI associated with complex C: in all nine sightlines projected onto that HVC it is detected, although in three of these the O VI only extends out to the velocity where the HI peaks. In one sightline through complex A a weak O VI-HVC can be seen. The Magellanic Stream is detected toward Fairall 9. In eight other cases a HI HVC lies just a few degrees away and has a velocity similar to that of the high-velocity O VI. Twelve sightlines lie in the region $l=180^\circ-330^\circ$, $b>35^\circ$ and show absorption at velocities $>+200 \text{ km s}^{-1}$. Another eleven lie in the region $l=20^\circ-140^\circ$, $b<-30^\circ$ and show absorption at velocities ranging from -400 to -150 km s^{-1} (six of the sightlines near a HI HVC probably also belong to this group). Apart from these associations and groupings, there are 14 more sightlines with high-velocity O VI.

In the case of complex C a possible explanation for the associated O VI absorption is that its outer envelope is heated by friction while it moves closer

to the Galaxy. No explicit models of this process exist, however, and it will require the measurement of other highly-ionized atoms, such as N V and C IV to discern between the possible explanations.

The concentration of twelve sightlines with high-positive O VI lies diametrically opposed to the concentration of seventeen with high-negative O VI absorption. The latter lies near the direction to M 31 and other Local Group galaxies, which may indicate that we are detecting a filament of hot gas in the Local Group through which the Milky Way is moving. A more detailed analysis of the velocities and distribution of high-velocity O VI will be needed to confirm this possibility.

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